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MATCHED FILTERING WITH ACHROMATIC OPTICAL CORRELATORS

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Research Directorate
US Army Missile Laboratory

23 February 1982

U.S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An achromatic Fourier transform system for use in an optical correlator has been designed and used with incoherent light to obtain autocorrelations of pictures of aerial views of urban areas. The necessary optics included achromatic lenses and some highly achromatic holographic elements in a unique arrangement to produce wavelength independent Fourier transforms.

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CONTENTS

I. INTRODUCTION

Infrared-emitting diodes have high power output, small spatially incoherent radiating surfaces, and potentially low price that would make them useful as radiation sources for coherent optical correlators. Limited spatial coherence reduces alignment accuracy requirements, and to some extent, also scale and orientation accuracy. One limitation of the diode is that it has too broad a bandwidth to be used in a typical coherent correlator.

The basic Fourier transform relationship of a typical coherent optical correlator contains wavelength as one of the factors: the transform scale is proportional to wavelength. With a broadband radiation source, only the transform generated by a narrow portion of the bandwidth matches the scale of the filter. To correct this problem, an achromatic Fourier transform system is needed.

This report compares and evaluates two achromatic Fourier transform systems described in the literature. The performance of the simplest system is estimated and experiments performed with it are described. A bibliography of recent reports and publications on coherent optical correlators from the Research Directorate, United States Army Missile Command at Redstone Arsenal, Alabama, in included.

II. ANALYSIS AND COMPARISON OF PROPOSED ACHROMATIC FOURIER TRANSFORM SYSTEMS

Three publications contain the original derivations and descriptions of achromatic Fourier transform systems. The first by Katyl[1] describes a system in which lateral and axial magnification is held constant and an approximate optical system for implementing it is described. Morris[2] uses a somewhat similar approach but with great detail and a thorough analysis. He also proposes how to implement the system with greater accuracy than in Katyl's paper. Collins[3] uses a linear system analysis approach and includes error analysis of an approximate implementation of his system.

In order to compare the expected performance of the Morris and Collins achromatic Fourier transform systems, a ray tracing analysis approach was used. Figures 1(a) and (b) show the two systems. A ray originates at the input plane at a distance y_1 above the axis in a direction determined both by the frequency of an assumed test grating and the wavelength of radiation. An equation is then written for the intercept of this ray with the output plane assuming perfect thin lenses and using small angle approximations. The equations used for these calculations are as follows:

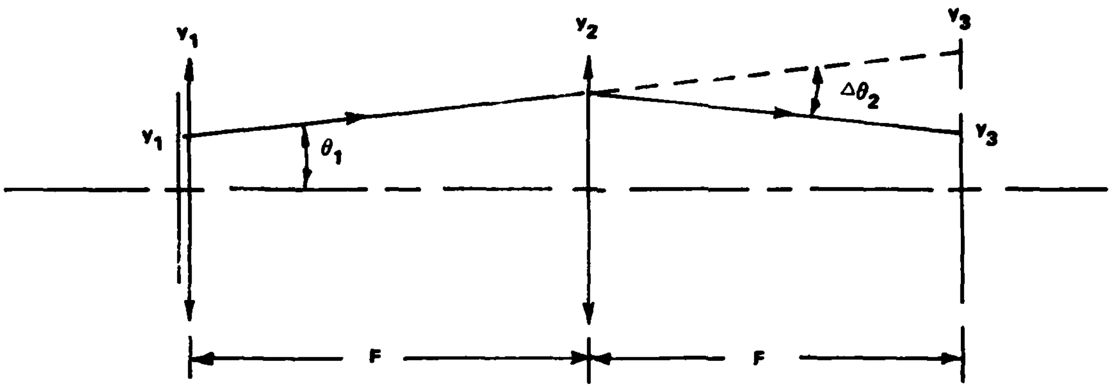
$$\theta_1 = \lambda f - y_1/F_1 \quad (1)$$

---

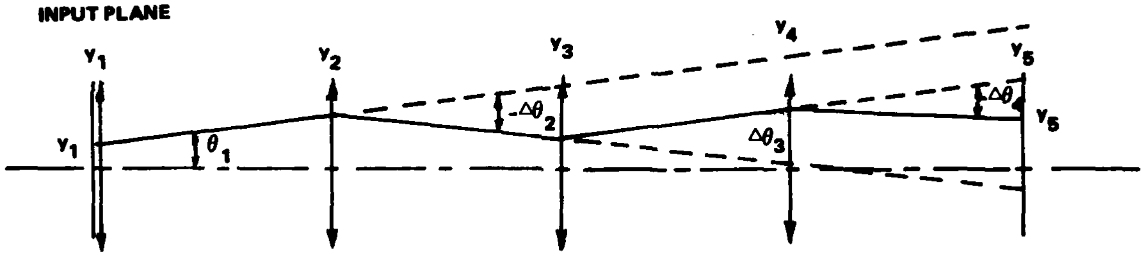
[1]Robert H. Katyl, "Compensating Optical Systems. Part 3: Achromatic Fourier Transformation," Appl. Opt. 11, p. 1255 (May 1972).

[2]G. M. Morris, "Diffraction Theory from Achromatic Fourier Transformation," Appl. Opt. 20, p. 2017 (June 1981).

[3]G. D. Collins, "Achromatic Fourier Transform Holography," Appl. Opt. 20, p. 3109 (September 1981).



(a) Morris System.



(b) Collins System.

Figure 1. Geometry for ray trace analysis of achromatic Fourier transform.

where λ is the wavelength of light, f is the spatial frequency of the test grating and $-y_1/F_1$ is the angular ray direction change by the lens of focal length F_1 in contact with the grating. At other lenses, the ray direction change $\Delta\theta$ is given by

$$\Delta\theta = -y/F \quad , \tag{2}$$

where y is the ray intercept of the lens and F is the focal length.

An expression for the ray y_3 intercept at the last, the Fourier transform, plane is given for Figure 1(a) by

$$y_3 = y_1 + 2F\theta_1 + F\Delta\theta_2 \quad , \tag{3}$$

where

$$\Delta\theta_2 = -y_2/F_2 = -(y_1 + \lambda fF - y_1F/F_1)/F_2 \quad . \tag{4}$$

Substitutions of Equations (1) and (4) into Equation (3) yields the result

$$y_3 = \lambda fF(2 - F/F_2) + y_1(1 - 2F/F_1 - F/F_2 + F^2/F_1F_2) \quad . \tag{5}$$

The desired result is to have y_3 independent of λ and y_1, or

$$y_3 = \lambda_o fF \quad , \tag{6}$$

which implies that the coefficient of y_1 in Equation (5) should equal to zero. Equating Equation (5) to Equation (6) yields the required focal lengths of the two lenses:

$$1/F_1 = (1/F)(1 - \lambda/\lambda_o) \tag{7}$$

$$1/F_2 = (1/F)(2 - \lambda_o/\lambda) \quad . \tag{8}$$

These results are the same as derived by Morris in Equations (18) and (19). Since y_3 is independent of y_1, the achromatization is space invariant. The first lens, described by Equation (7), consists of a position achromat of focal length F and negative lens whose focal length is inversely proportional to the wavelength of light, $-F\lambda_o/\lambda$. This element is a holographic lens.

The second lens described by Equation (8) consists of a positive achromat of focal length F/2 and a negative lens whose focal length is proportional to the wavelength of light, $-F\lambda/\lambda_o$. This lens cannot be easily implemented, although Morris has designed a rather exact approximation. The above lens combination can be roughly approximated by a single element holographic lens.

This can be explained as follows: let $\lambda = \lambda_o + \Delta\lambda$ which then gives

$$2 - \lambda_o/\lambda = 1 + \Delta\lambda/\lambda_o - (\Delta\lambda/\lambda_o)^2 + . . . \tag{9}$$

as the required coefficient of 1/F. If instead, the coefficient of 1/F is that of a holographic lens, λ/λ_o, then

$$\lambda/\lambda_o = 1 + \Delta\lambda/\lambda_o \quad . \tag{10}$$

Thus, the first two terms of Equation (1) are the same as those of Equation (9), while the higher order terms of Equation (9) are not generated by the holographic lens.

The achromatic Fourier transform system derived by Collins can be analyzed in a similar way. Because this system contains two achromatic lenses besides the two initially unspecified lenses, the derivation is much more complex. The equations for Figure 1(b) are:

$$y_5 = y_1 + 4F\theta_1 + 3F\Delta\theta_2 + 2F\Delta\theta_3 + F\Delta\theta_4 \tag{11}$$

$$\theta_1 = f\lambda - y_1/F_1 \tag{12}$$

$$\Delta\theta_2 = -y_2/F_2 = -(y_1 + F\theta_o)/F_2 \tag{13}$$

$$\Delta\theta_3 = -y_3/F_3 = -(y_1 + 2F\theta_1 + F\Delta\theta_2)/F_3 \tag{14}$$

$$\Delta\theta_4 = -y_4/F_4 = -(y_1 + 3F\theta_1 + 2F\Delta\theta_2 + F\Delta\theta_3)/F_4 \quad . \tag{15}$$

Equations (11) through (15) yield an expression for y_5:

$$y_5 = -\lambda fF(F/F_3) + y_1[-1 = F^2/(F_1F_3)] \quad . \tag{16}$$

Letting $y_5 = \lambda_o fF$ and setting the coefficient of $y_1 = 0$, we can solve for the two unspecified focal lengths:

$$1/F_1 = -(1/F)(\lambda/\lambda_o) \tag{17}$$

$$1/F_3 = -(1/F)(\lambda_o/\lambda) \quad . \tag{18}$$

As before, the first lens contains a negative holographic lens but without the achromat; the second lens again requires a lens where focal length is proportional to the wavelength of light. This lens can be approximated by the lens

$$1/F_3 = 1/F(-2 + \lambda/\lambda_o) \tag{19}$$

consisting of a negative achromat of focal length F/2 and a positive holographic zone plate of focal length $F\lambda_o/\lambda$.

Comparison of Equations (7) and (8) with Equations (17) and (18) shows that both systems require the same type of lenses: one holographic lens and one with focal length proportional to wavelength. In this respect, both systems are similar. Since the Morris proposed system has 2F overall length while the Collins system has 4F length and, besides that, needs two additional achromatic lenses, the Morris system was selected. Several additional calculations were made about the Morris system.

A spacing was introduced between the object plane and the first lens in Figure 1(a). The calculated values were the same as in Equations (7) and (8), indicating the achromatization is independent of input image position.

A grating was added halfway between the first and second lens element as shown in Figure 2. Using small angle approximations and choosing the carrier frequencies of lens F_1 and F_3 to be half of the grating frequency at plane 2, again the same expressions were found for F_1 and F_3. This indicates that the required holographic lenses could be recorded on a carrier frequency without destroying the achromatic properties of the system.

Also, Equation (20) in the Morris paper was examined. This equation indicates that an achromat plus a negative holographic lens is needed to correct for residual phase errors. The negative holographic lens could be implemented by recording the matched filter with a diverging reference beam, as in Figure 3. The achromatic lens is of no importance since, typically, an achromatic lens is used anyway to focus the diffracted beam.

Finally, the achromatized system was compared with a chromatic Fourier transform system. In the chromatic system, the ray intercept is given by

$$\begin{aligned} y &= \lambda f F \\ &= \lambda_o f F(1 + \Delta\lambda/\lambda_o) \quad , \end{aligned} \tag{20}$$

where the $\Delta\lambda/\lambda_o$ term represents an error. A similar expression can be derived for the achromatized Morris system using two holographic lenses:

$$y = \lambda_o f F \, [1 - (\Delta\lambda/\lambda_o)^2] \quad . \tag{21}$$

Thus, the error is reduced by the factor $\Delta\lambda/\lambda_o$. Since the expression

$$N = \lambda/\Delta\lambda \tag{22}$$

was presiously derived[4,5] where N is the number of resolved points that can

[4]J. Upatnieks, "Optical Correlator with Laser Diode Sources," Final Report for Battelee Task Order No. 1095 (October 1979).

[5]J. G. Duthie, J. Upatnieks, C. R. Christensen, and R. D. McKenzie, Jr., "Real-Time Optical Correlators with Solid-State Sources," SPIE Vol. 231, International Optical Computing Conference (1980).

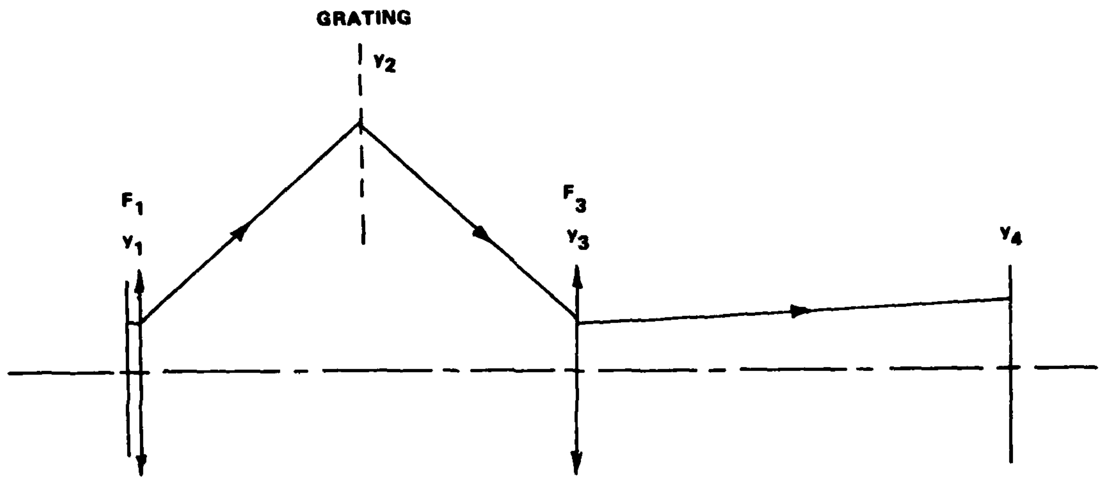


Figure 2. Modified Morris achromatic Fourier transform system.

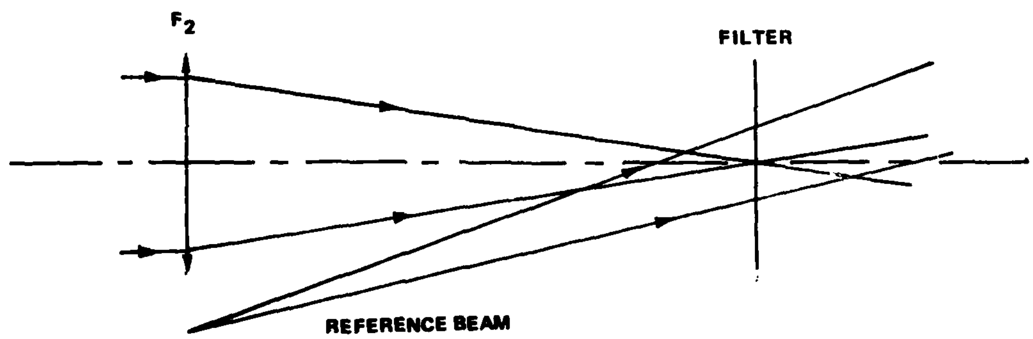


Figure 3. Filter recording geometry that includes the equivalent of a negative holographic lens.

be correlated by a light source of bandwidth $\Delta\lambda$, then it is reasonable to deduce from Equations (20) to (22) above that

$$N = (\lambda/\Delta\lambda)^2 \tag{23}$$

for the approximate achromatic system.

III. EXPERIMENTS

Figure 4 shows the achromatic Fourier transform coherent optical correlator that was assembled. Two holographic lenses were recorded on Kodak 649F emulsions in dichromated gelatin, as was the grating. The carrier frequencies of the two holographic lenses were the same, and the grating frequency was twice that of the lenses. This system prevented the undiffracted light from reaching the Fourier transform plane. An argon laser was set up nearby so that either a mercury arc lamp or the laser could be used as the light source.

After the system was set up, the point focus of the light source was observed in the Fourier transform plane with a microscope. With a spectrally unfiltered mercury arc lamp as the source, a slight chromatic aberration was visible. It was found that this aberration could be corrected by adjusting the position of lens L_1 which caused the light incident on the input plane to be noncollimated.

Two crossed Ronchi rulings were then inserted at the input plane and the Fourier transform was observed. Some chromatic dispersion was visible which could be corrected by adjusting the spacing between lens L_2, L_3, and the grating. The required adjustment for the two orthogonal directions of the transform was somewhat different, thus complete correction could be achieved for only one direction. Figure 5(a) shows a photograph of the spectrum with a chromatic Fourier transform system and Figure 5(b) shows the spectrum taken with the achromatic Fourier transform system.

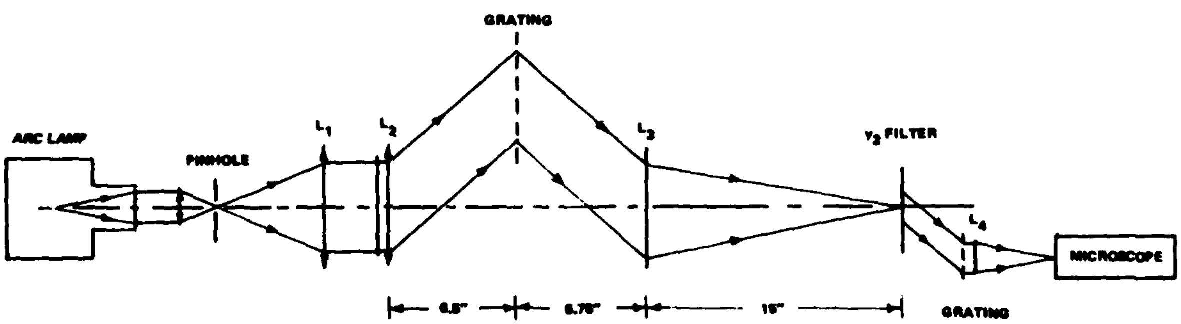
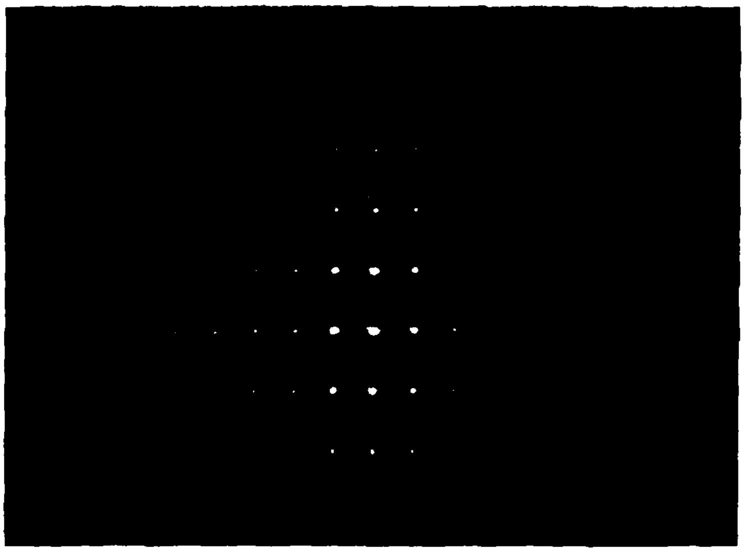
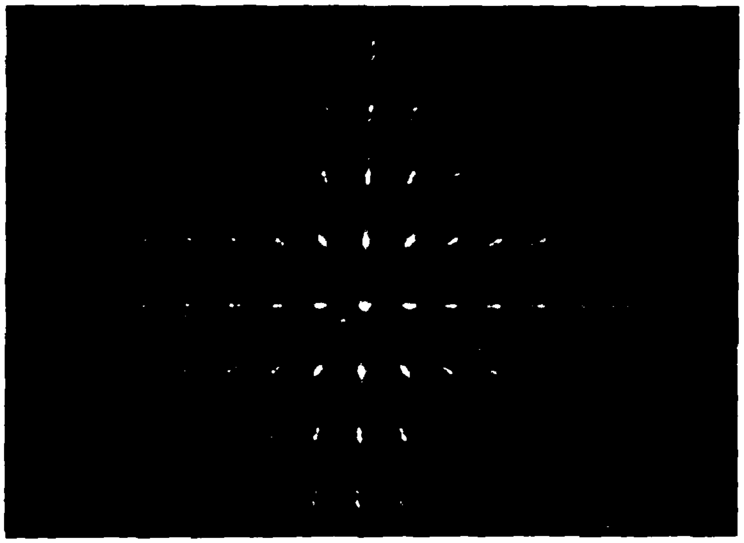


Figure 4. Experimental achromatic Fourier transform system.



(a)



(b)

Figure 5. Fourier transforms of two crossed gratings: (a) with chromatic system and (b) with achromatic system. The Ronchi rulings had 8 1/mm and 10 1/mm frequency, and the light source was a mercury arc lamp.

Several matched filters were constructed of an aerial view of Huntsville, Alabama, with an argon laser light source operating at 514.5 nm wavelength. Correlations were obtained both the the argon laser as well as with the spectrally unfiltered mercury arc lamp. Figure 6 shows the correlation lines formed by the mercury green line at 546 nm and the amber line at 578 nm simultaneously. Similar results were obtained laser year[6] with the mercury arc lamp and a chromatic Fourier transform system. In that case, however, correlation could be obtained at one wavelength at a time.

Correlations with a mercury arc lamp could be observed only when an ordinary matched filter was copied onto dichromated gelatin to improve its efficiency. Even then, the light level was very low and measurements with a TV camera and line scan recording could not be made. Overall light efficiency of the achromatic system was lower than that of a chromatic system because the holographic lenses and the grating were somewhat lossy, with about 25 percent overall efficiency.

Several observations were made concerning the achromatic correlator:

- With argon laser green light, about 0.02 $\mu W/cm^2$ object illumination was needed to form a barely visible correlation spot.

- With a 1000-watt mercury arc lamp, 380-mm focal length collimating lens and 25-μm diameter pinhole filter, the object irradiance was at 0.7 to 1.5 $\mu W/cm^2$ at the object plane.

- Comparison of the correlation peaks obtained with 25-μm and 100-μm diameter pinholes showed a slight increase in correlation spot diameter with the 100-μm diameter pinhole. This effect was probably caused by imperfect achromatization of the system.

- Best correlations were obtained with an object transparency that was an aerial photograph of Huntsville, Alabama. This photograph contained high spatial frequencies.

- The holographic lenses had several deficiencies: considerable light scattering and less than maximum possible diffraction efficiency. In coherent light, the scattered light strongly correlated with the filter; in broad-spectrum light, only the object correlated because the noise was not achromatized.

- Although the holographic elements had very high efficiencies when measured in the monochromatic light in which they were made, the diffraction efficiencies were strongly wavelength dependent since the Bragg condition was satisfied only for one wavelength. However, in an application using a high power light emitting diode, which has a relatively narrow bandwidth, this may not be as bothersome a deficiency as with the mercury arc lamp source.

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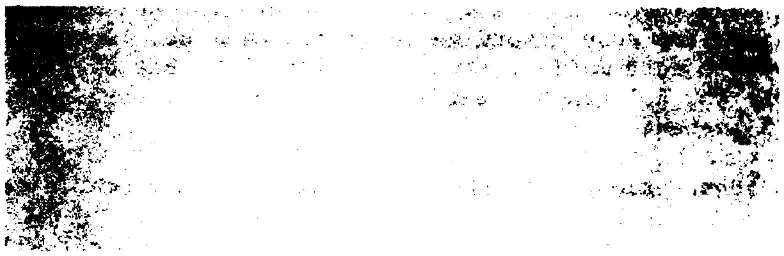
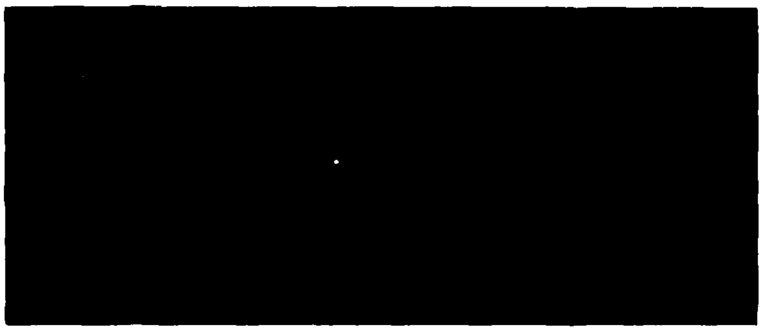
[6] J. Upatnieks, "Coherent Optical Correlation with Semicoherent Light Sources," Final Report for Battelle Delivery Order No. 1432 (December 1980).



(a)



(b)

Figure 6. Correlations obtained with the achromatic Fourier transform system: (a) dispersed correlation peak and (b) integrated correlation peak with a mercury arc lamp.

IV. SUMMARY AND CONCLUSIONS

A ray tracing method of analysis was developed and applied to the two proposed achromatic Fourier transform systems. The analysis indicated that both proposed systems should work equally well. The needed wavelength dispersive elements can be approximated with holographic optical elements (HOE's). A modification was introduced to the simplest of the two systems: a grating was added which allowed the HOE's to be recorded on a carrier and without a grating in contact with each of the two elements. This arrangement allowed a reduction of the needed diffractive elements from four to three, and prevented undiffracted light from reaching the Fourier transform plane.

An achromatic Fourier transform system was assembled and tested. Correction of chromatic dispersion of focus and frequency spectrum were achieved over approximately 32 nm bandwidth at a center wavelength of 562 nm. Matched filters were fabricated and correlations were achieved with broadband light over 32 nm bandwidth. The correlation peak was difficult to observe due to low light outputs of the lamp and the losses by the HOE's.

Improved results should be possible by making several improvements in the system. First, the efficiency of the HOE's and gratings should be improved and scattering level should be decreased. Second, a brighter light source, such as the Ozram 100-watt mercury lamp, in conjunction with low-aberration imaging lenses, should be used. The potential increase in available light with the lamp is at least a factor of five. Matched filters should be recorded on dichromated gelatin and their efficiency optimized to the frequency band corresponding to the object.

Many questions remain unanswered concerning the achromatic Fourier transform system. All of the analysis to date is based on idealized thin lens and small angle approximations. More thorough analysis is needed to determine its expected performance and limitations. Such analysis could be done, for example, with ray tracing programs such as the HOAD. Precise experimental investigation also would be useful. The HOE elements and gratings should be fabricated and tested with the same care as high-quality lenses before they are used in an optical system.

The experiments described here proved that correlators can be achromatized over the bandwidth range of a typical infrared-emitting diode. However, the construction of the required HOE's and alignment of the system at an invisible wavelength will not be a simple task.

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Dr. J. G. Duthie	80
-RPR	15
-RPT	1

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